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Irradiation tests at cryogenic temperatures on diffusion type diodes for the LHC superconducting magnet protection

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Abstract

Within the framework of the LHC magnet protection system, the irradiation hardness of high current by-pass diodes is subject to examination. The relocation of these diodes and recent calculations give rather low irradiation levels for the position of the diodes. This offers the possibility to replace the originally foreseen epitaxial type diodes by diffusion type diodes. Therefore, different types of 75mm diffusion diodes were submitted to an irradiation test program. One part of the experiments was performed in the Munich Research Reactor. Further irradiation tests were carried out in the northern fixed target area of the SPS accelerator at CERN.

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Within the framework of the LHC magnet protection system, the irradiation hardness of high current by-pass diodes is subject to examination. The relocation of these diodes and recent calculations give rather low irradiation levels for the position of the diodes. This offers the possibility to replace the originally foreseen epitaxial type diodes by diffusion type diodes. Therefore, different types of 75mm diffusion diodes were submitted to an irradiation test program. One part of the experiments was performed in the Munich Research Reactor. Further irradiation tests were carried out in the northern fixed target area of the SPS accelerator at CERN.

1 INTRODUCTION

In the LHC magnet protection system, cold power diodes are foreseen to by-pass the current during a quench of a magnet. As these diodes are mounted inside the LHC cold mass relatively close to the beam, they are exposed to radiation resulting from proton losses and beam gas interactions. Recent calculation [1] gives the following radiation levels:

- Quadrupole position: lifetime (10 years) dose: 180Gy; lifetime neutron fluence: $1.2 \cdot 10^{12}$cm^{-2}. Hereby it has to be stated that the radiation levels may vary by a factor of 10 over the area covered by the device.
- Dipole position: lifetime (10 years) dose: 30Gy; lifetime neutron fluence: $1.5 \cdot 10^{11}$cm^{-2}

These results offer the possibility to use diffusion type power diodes instead of epitaxial diodes. Despite the fact, that diffusion type power diodes are known to be more sensitive to irradiation, they have in general higher reverse blocking voltages and higher turn-on voltages at liquid helium temperature than epitaxial ones ($V_{todiff} \approx 8$V compared to $V_{toepi} \approx 1.5$V [2]). Because of the high turn-on voltage, only one diode per dipole magnet instead of two diodes in series is required.

2 IRRADIATION TESTS IN AN ACCELERATOR ENVIRONMENT

Different types of 75mm diffusion type power diodes, manufactured by EUPEC/Germany, MITEL and WESTCODE/England, were exposed to irradiation in the north target area of the CERN SPS accelerator at liquid nitrogen temperature. By positioning the samples close to the fixed beryllium target T4, the spectrum of the received irradiation resembles that expected in the LHC. An overall dose of about 1kGy and a fast neutron fluence of 1.0×10^{12}cm^{-2} was applied within several irradiation periods. After each step, the device parameters were measured under forward and reverse bias. One part of the samples was also warmed up to room temperature after each irradiation step, in order to study the effect of partial annealing of the irradiation induced defects. Having completed the irradiation tests, four samples underwent a high current endurance test.

2.1 Increase of the forward voltage after irradiation at T=77K

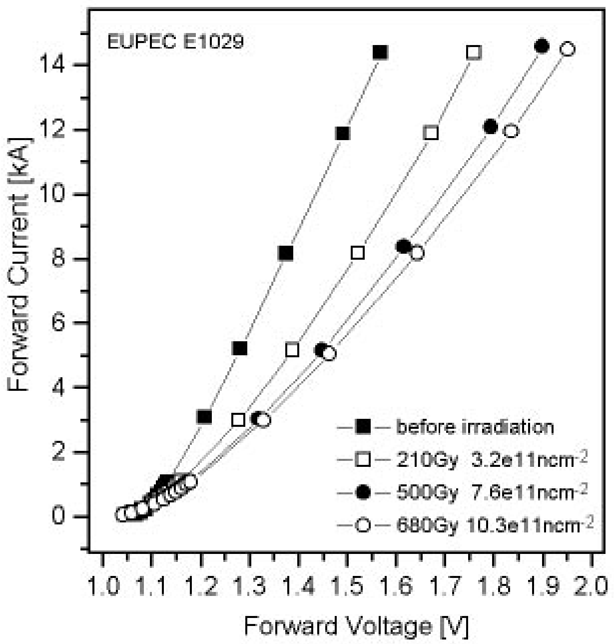

Figure 1 Increase of the forward voltage U_f (I,T=77K) of a diffusion type power diode after irradiation at T=77K. The legend shows the accumulated energy dose and the total fast neutron fluence.

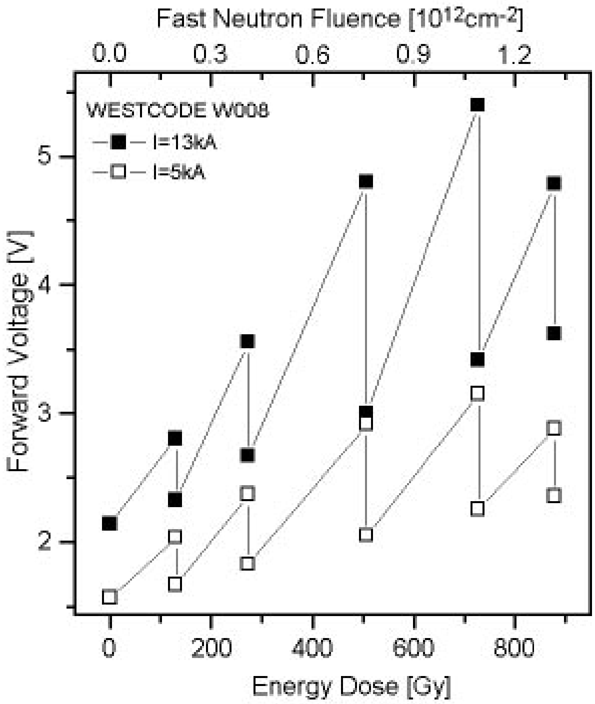

Figure 2 Forward voltage U_f (I=const.,T=77K) of a diffusion type power diode as a function of the received dose. This diode was warmed up to room temperature after each irradiation step. The data are presented for two different fixed currents.

Figure 1 and 2 show typical examples of the altered forward characteristic of a power diode due to irradiation induced defects. The data were analysed with the Shockley equation including the series resistance of the device.

$$I_f = I_s\left[\exp\left(\frac{U_f - R_{series} I_f}{\eta V_t}\right) - 1\right]; \quad V_t = \frac{k_B T}{e}; \quad \eta \cong 2$$

The diode quality factor, which takes in account the different contributions to the diode current, is η=1 for pure diffusion current, and η=2 if the recombination current is dominating. At liquid nitrogen temperature the diffusion current is marginal and η=2. In a first approximation the series resistance, resulting from the bulk resistivity of the quasi-neutral regions of the diode, increases linearly with the fast neutron fluence. However, there is a remarkable variance across the different diode types (table 1). The reason is the different base width of the devices, which in turn has its origin in variations of the doping profile and the doping concentration.

Diode type	$\Delta R_{series}[\mu\Omega/10^{12}ncm^{-2}]$
EUPEC (4 diodes)	45
MITEL TYPE 1 (2 diodes)	43
MITEL TYPE 2 (2 diodes)	27
WESTCODE (2 diodes)	405

Table 1 Increase of the series resistance after irradiation at T=77K in an accelerator environment. A fast neutron fluence of $10^{12}ncm^{-2}$ corresponds to an energy dose of 650Gy.

2.2 Tests under reverse bias

The reverse blocking capability was tested under current and voltage control (I_{rmax}=1mA, U_{rmax}=1kV) at T=77K after each irradiation step. From these data the maximum reverse voltage before the onset of the avalanche breakdown was deduced (table 2). Irradiation induced defects in the depleted zone increase the threshold field for the avalanche breakdown, resulting in a higher reverse blocking voltage.

Diode type	ΔU_{rmax}[%/kGy]
EUPEC (4 diodes)	3
MITEL TYPE 1 (2 diodes)	1
MITEL TYPE 2 (2 diodes)	2
WESTCODE (2 diodes)	59

Table 2 Increase of the maximum reverse blocking voltage U_{rmax} (T=77K) after irradiation.

2.3 Annealing after irradiation

Some of the diodes were warmed up to room temperature after each irradiation step, in order to investigate the influence of thermal annealing of irradiation induced defects to the device parameters such as the series resistance. The remarkable annealing rates (table 3) are similar for different diode types and qualify thermal annealing as a tool to recover irradiated diodes (see also figures 2 and 4).

Diode	EUPEC I	EUPEC II	WESTCODE I	WESTCODE II
$\Delta R_{irr}/\Delta R_{annealing}$[%] T=77K$\rightarrow$T=293K	76	51	76	81

Table 3 Annealing rates based on the diode series resistance at T=77K for two different diode types.

2.4 Endurance tests with irradiated power diodes

During a magnet quench and the following discharge of the complete magnet chain, the bypassing diode has to withstand an exponentially decaying current, starting at I_0=13kA with a time constant τ=100s for the dipole and τ=50s for the quadrupole magnets. High current endurance tests at liquid helium temperature [2] are performed within the standard diode test program to ensure that the devices meet these requirements.

The tests with irradiated diodes were intended to get upper limits for the series resistance and the turn-on voltage. In the tests performed to date (table 4), we observed a short circuit on one diode (EDD8), whereas another diode (W006), exhibiting a similar series resistance, passed the test. The reasons are the smaller size of the EDD8 housing, containing about 30% less copper than the W006 housing, and a very high turn-on voltage of the diode. On the three diodes which passed the test, thermal annealing during the endurance test was observed.

Diode	EDD8	E1024	E1032	W006
Vto(T=4.2K)[V]	26.6	8.6	7.1	9.1
R_{series}(T=77K)[$\mu\Omega$]	220	42	44	231
Test	Short circuit	Passed	Passed	Passed

Table 4 Turn-on voltage and series resistance of irradiated diodes submitted to an endurance test.

3 IRRADIATION TESTS IN A NUCLEAR REACTOR

The response of the diodes to irradiation at liquid helium temperature was studied with the help of the low temperature irradiation facility of the Munich Research Reactor [3]. Hereby especially the alteration of the turn-on voltage V_{to} (T=4.2K) after irradiation at low temperature was subject to test. It is noteworthy that the turn-on voltage is probably the only device parameter which can be measured once the diode is installed in the LHC. As the sample size for the irradiation tests in Munich is limited, specially fabricated small (10mm in diameter) diode samples were used. After each irradiation inside the reactor core the turn-on voltage of the devices was measured (figure 3), showing the same trend in irradiation hardness as the tests of the full size diodes. Some diodes were also warmed up to room temperature after irradiation, with the result of a remarkable decrease of the V_{to} (T=4.2K) due to thermal annealing (figure 4).

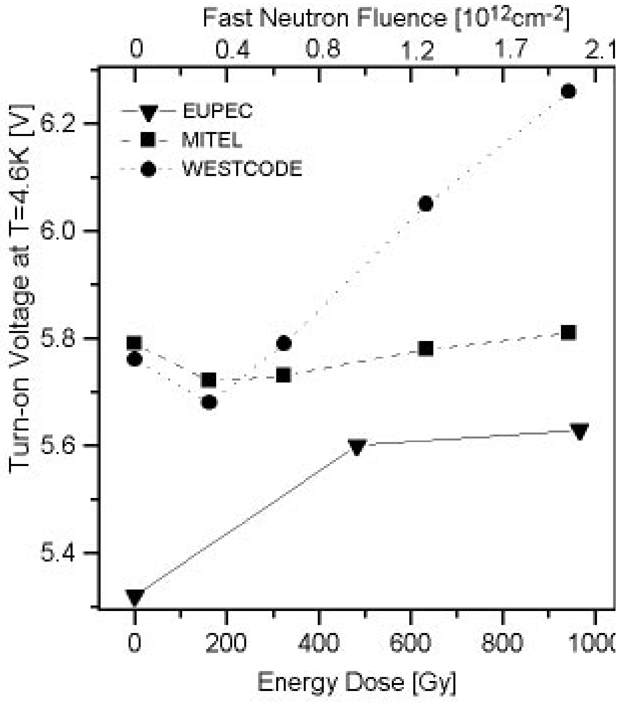

Figure 3 Turn-on voltage V_{to} (T=4.6K) of different types of small diode samples used in the irradiations in a nuclear reactor as a function of the energy dose and the fast neutron fluence.

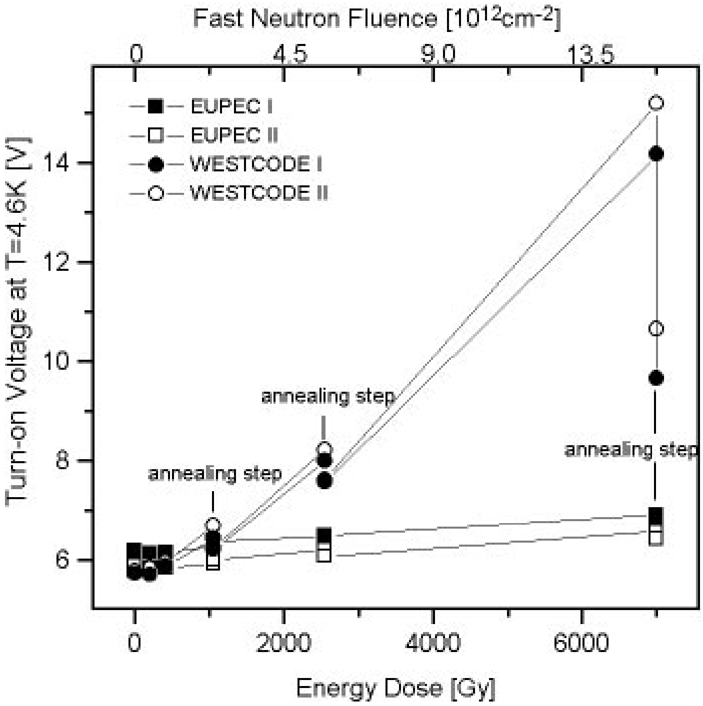

Figure 4 Turn-on voltage V_{to} (T=4.6K) of different types of small diode samples after low temperature irradiation in a nuclear reactor with intermediate warm up to room temperature.

4 CONCLUSIONS

With respect to the requirements of the magnet protection system, the results of the tests give clear evidence, that the EUPEC and MITEL diffused diode types can be regarded as radiation hard up to an energy dose of about 1kGy corresponding to a fast neutron fluence of $1.3\times10^{12}cm^{-2.}$ They are therefore suitable for protection of the quadrupole magnets. In contrast to these diodes the WESTCODE diffusion type diode is much more sensitive to radiation and should be foreseen only to protect the dipole magnets.

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6 REFERENCES

[1] Stevenson, G. private communication
[2] Coull, L., Denz, R. and Hagedorn, D. High Current Diffusion Type Diodes at Cryogenic Temperatures for the LHC Superconducting Magnet Protection, LHC Project Report 131 (1997)
[3] Gerstenberg, H. and Gläser, W. Neutron Irradiation at Temperatures below 6K at the Munich Research Reactor (FRM), Nuclear Science and Engineering (1992) 110 50-55